DOCUMENT RESUME

ED 270 858 EA 018 536

AUTHOR Hutchinson, Nancy L.
TITLE A Critical Analysis and Examination of Research Relevant to Glaser's "Education and Thinking: The Role of Knowledge."
PUB DATE May 85
NOTE 39p.; Paper presented at the Annual Meeting of the Canadian Society for the Study of Education (Montreal, Quebec, Canada, May 1985).
PUB TYPE Viewpoints (120) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS Cognitive Development; *Cognitive Processes; Cognitive Structures; Elementary Secondary Education; Foreign Countries; Learning Processes; Learning Strategies; *Learning Theories; Logical Thinking; Mathematics Curriculum; Physics; *Problem Solving; Research Needs; Science Curriculum; Social Studies; Teaching Methods
IDENTIFIERS *Glaser (Robert)

ABSTRACT

This paper begins with a summary and analysis of Robert Glaser's arguments, presented in his paper "Education and Thinking: The Role of Knowledge," which contend there are strong interactions between structures of knowledge and cognitive processes, and that problem solving and reasoning are taught best in the context of the acquisition of domain-specific knowledge. Glaser's arguments are considered in light of evidence, cited in his 1984 paper, from three sources: developmental psychology, studies of expert and novice problem solving, and process analyses of intelligence and aptitude tasks. The paper then seeks to translate six of Glaser's claims about expertise in problem solving into testable hypotheses. Evidence in support of these hypotheses is then cited from three curricular domains: physics, mathematics, and social studies. In each of these areas, the differences between novices and experts point to a relationship between structures of knowledge and cognitive processes. It is concluded that although Glaser's hypotheses have received tentative support from novice-expert studies in three curricular areas, more research is needed to investigate the validity of Glaser's assertions. Four pages of references are included. (TE)

****
* Reproductions supplied by EDRS are the best that can be made *
* from the original document. *
****

U.S. DEPARTMENT OF EDUCATION
Office of Educational Research and Improvement
EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)

This document has been reproduced as received from the person or organization originating it.

Minor changes have been made to improve reproduction quality.

• Points of view or opinions stated in this document do not necessarily represent official OERI position or policy

"PERMISSION TO REPRODUCE THIS MATERIAL HAS BEEN GRANTED BY

Nancy L. Hutchinson

TO THE EDUCATIONAL RESOURCES INFORMATION CENTER (ERIC)."

ED270858

A Critical Analysis and Examination of Research Relevant to Glaser's "Education and Thinking: The Role of Knowledge"

Nancy L. Hutchinson
Instructional Psychology Research Group
Simon Fraser University

Presented at CSSE
Montreal, Canada
May, 1985

Running head: EDUCATION AND THINKING

EA 018 536

The author would like to thank Phil Winne, Pete Hemingway and John Walsh for their helpful comments on the manuscript.

A Critical Analysis and Consideration of Research Relevant to Glaser's "Education and Thinking: the Role of Knowledge"

Robert Glaser published in American Psychologist (1984) an expanded version of his Edward L. Thorndike address presented to the American Psychological Association in 1982. He began "A significant part of current investigation in cognitive psychology concerns the ability of people to reason, understand, solve problems and learn on the basis of these cognitive activities." Glaser reached the conclusion that these abilities would be enhanced most effectively if they were developed explicitly in the process of acquiring the domain knowledge and skills which are considered the objectives of education and training. He asserted that many earlier investigations in cognitive psychology had explored "knowlege-lean" problems and therefore offer limited insight into learning and thinking that involve domain-specific knowledge. He claimed, in contrast, that recent work on problem solving in "knowlege-rich" domains has shown strong interactions between structures of knowledge and cognitive processes.

This paper has two purposes. The first purpose is to summarize and analyze critically Glaser's arguments that there are strong interactions between structures of knowledge and cognitive processes, and that problem solving and reasoning are taught best in the context of acquisition of domain knowledge. Glaser's arguments will be considered in light of the evidence he cited in his 1984 paper. This came from three sources: developmental psychology, studies of expert and novice problem solving, and process analyses of intelligence and aptitude tasks.

The second purpose of this paper is to translate Glaser's claims about expertise in problem solving into testable hypotheses, and examine the empirical support in knowledge-rich domains. I have selected six particular assertions from Glaser's paper because I think his paper is not really concerned with the general issues of "Education and Thinking", but rather with "Instruction in Problem Solving: The Role of Knowledge". The paper concerns the implications that can be drawn for instruction in problem solving from findings about the major role that knowledge plays in expert problem solving. These assertions of Glaser's about the role of knowledge in problem solving require support because they are the foundation upon which the implications for instruction are built. However, I feel that Glaser's indefinite statements of these assertions require discussion and some clarification before they can be considered testable hypotheses or falsifiable statements. When making claims that problem solving in schools should be taught in the context of domain specific knowledge, it seems to me that one ought to examine the evidence for the claimed interactions within knowledge domains usually taught in schools. Before accepting Glaser's recommendations for how to improve instruction in their knowledge domains, educators ought to examine the evidence. I will seek support for these hypotheses in research comparing novice and expert problem solving in three domains taught in schools: mathematics, science, and social studies. (See Table 1).

My intent is not to dismiss or discredit Glaser's considerable theoretical and empirical contributions. In fact, I share his desire for more thinking and higher-order processing in schools. I think it is important to focus on <u>both</u> the acquisition and organization of declarative knowledge <u>and</u> the acquisition of procedural knowledge in education. However, cognitive psychology is in danger of making the mistake we attribute to the behaviorists

Table 1.
Summary of Evidence for Glaser's Assertions in Three Curricular Areas

Curricular Areas and Studies	Assertion 1	Assertion 2	Assertion 3	Assertion 4	Assertion 5	Assertion 6
	There are strong interactions between structure of knowledge and cognitive processes.	Better problem solvers characterized by "possession and utilization of an organized body of conceptual and procedural knowledge"	"Knowledge of novices is organized around the literal objects given in the problem statement."	"Experts' knowledge is organized around principles and abstractions that subsume these objects"	"Novices show effective heuristics"	Novices show inability to infer further knowledge from the literal cues in the problem statement."
PHYSICS Simon & Simon (1978)	Condition-action statements of experts and novices differed.	The experts solved problems quickly with few errors.			Novices used subgoals and worked backwards in solving problems.	
Chi, Feltovich & Glaser (1981)	Condition-action statements in experts' protocols, but not in novices' protocols	Experts' network representations were hierarchically organized: principles, conditions, variables. Experts sorted slowly with few errors.	Novices sorted problems by keywords or visual configurations in problems.	Experts sorted problems by the principle that provided a solution - Newton's Second Law, etc.		Novices used literal cues such as "friction" and "gravity" to select variables and then formulae in bottom-up fashion.
Reif & Heller (1982)		Prescriptive analyses indicated organization in a hierarchical fashion necessary for knowledge base and condition-action statements.				
MATHEMATICS Hinsley, Hayes & Simon (1977)		Competent solvers were quick and consistent in categorizing problems.	Competent solvers categorized quickly on the basis of the first few words in a a problem.			Competents categorized on the basis of a few words given at the beginning of a problem.

BEST COPY AVAILABLE

Table 1. Continued
Summary of Evidence for Glaser's Assertions in Three Curricular Areas

Curricular Areas and studies	Assertion 1	Assertion 2	Assertion 3	Assertion 4	Assertion 5	Assertion 6
Silver (1979)			Less capable solvers sorted problems according to contextual details and question form.	More capable solvers sorted problems on basis of method of solution.		
Schoenfeld & Herrmann (1982)			Novices sorted problems on basis of words or objects given in problem statement.	Experts sorted problems by methods of solution such as pattern induction or linear equation.		
SOCIAL STUDIES						
Tyler & Voss (1982)	Knowledge dominated processing when content high in information and/or when it disagreed with expectations. Attitude dominated processing when low in information and in agreement with expectations					
Voss, Tyler & Yengo (1983)	Experts made great use of constraints (24% of protocol used to represent problem).	Experts generated an overall plan that was consistent and defensible from a particular perspective.	Novices made many claims about solutions to stated problems with little backing and few data.	Experts made arguments for and against their own claims appealing to data and principles (e.g. economic.)		
Voss, Greene, Post & Penner (1984)		Experts sought one general solution from which subproblems could be handled.		Experts explored ramifications of solutions and made arguments taking things to their logical conclusion.	Novices decomposed problems, and gave "sub-solutions" to numerous "sub-goals", often conflicting with one another.	

BEST COPY AVAILABLE

- jumping to far-ranging conclusions and recommending wide applications of what are as yet tentative hypotheses rather than established facts. Glaser's considerable reputation gives his assertions more weight than his arguments might earn. It is important to ask: what is known about the acquisition of expertise in curricular areas that might suggest the extent to which we ought to be persuaded by Glaser's (1984) paper?

Problem Solving

Educational institutions count as important among their purposes these two: imparting knowledge to their students, and preparing their students to solve problems. According to Polya, "...to have a problem means: to search consciously for some action appropriate to attain a clearly conceived, but not immediately attainable aim" (1981, p.117). A solution is "...a sequence of allowable actions that produces a completely specified goal expression" (Wickelgren, 1974, p.16).

How does one go about solving problems? Are the same approaches effective for all domains? Early work in cognitive science favoured the use of general heuristics. The problem solver employing a general heuristic, such as means-end analysis, repeatedly compares the present state with the desired state and asks, "What is the difference between where I am now and where I want to be? What can I do to reduce that difference?" Such questions result in a series of subgoals and actions to change the situation to approximate each subgoal. For example, Ernst and Newell (1969) published a case study containing the culmination of more than a decade's work on a single problem solving computer program, GPS (for General Problem Solver). They demonstrated that a performance program employing general heuristics, particularly means-end analysis, could solve a wide range of problems.

In the proceedings of a conference held at Carnegie-Mellon University in 1978 (Tuma & Reif, 1980), many of the participants referred to the dilemma of whether instruction in problem solving should be general and domain-independent or domain-specific. Greeno (1980) advocated that, with increasing knowledge about cognitive processing, the emphasis should be domain-specific. Students would learn problem solving in mathematics, then in physics, then in social studies, and so on. Simon (1980), on the other hand, concluded his presentation by asserting that with the vast changes in the world's knowledge that can take place in a student's professional lifetime, a strong case can be made for teaching and practicing general problem solving heuristics. Students would study problem solving, per se, and then learn its application in many areas. Larkin (1980) advocated research in domains that offered more complexity than games as well as more structure than real problems encountered in professional life - the domain of problems included in mathematics and science classrooms.

In summarizing the conference proceedings, Newell (1980) concluded that the basic controversy between domain-independence and domain-specificity remained unresolved. However, Glaser (1984) asserts that one of the two is definitely to be favoured in designing instruction to promote thinking - domain specificity.

Summary and Analysis of "Education and Thinking"

A Brief Consideration of Glaser's Arguments

Problem solving, reasoning, and understanding are investigated in cognitive psychology, along with people's ability to learn from these cognitive activities. Glaser argues that schools could benefit from the application of findings of cognitive psychology. He asserts that schools have been overly influenced by associationism and behaviorism, and that they teach

the "basics" without teaching thinking and problem solving. That problem solving and other higher-order processes are not being acquired by students has been reported (National Assessment of Educational Progress, 1981). However, there have been attempts to teach reasoning and problem solving. Glaser describes some of the better-known attempts at providing instruction in problem solving. All emphasize instruction in general reasoning and problem-solving heuristics independent of domain-specific knowledge. According to Glaser, these curricula and research on general heuristics "... used relatively knowledge-free problems, and as such offered limited insight into learning and thinking that require domain-specific knowledge" (p. 96,97). He does not address the question of the effectiveness of these programs, but refers to the general notion that general heuristics have wide applicability and low power.

Glaser argues that there are more recent studies in cognitive psychology that apply to situations where domain-specific knowledge is required. Recent work on problem solving in knowledge rich domains "shows very strong interactions between structures of knowledge and cognitive processes" (Glaser, 1984, p. 97) and forces us to consider the teaching of thinking in terms of knowledge and interactions between structures of knowledge and cognitive processes. Such a stance places great emphasis on the student's knowledge base. Some evidence for the focal role of knowledge comes from research in developmental psychology and in analogical reasoning. The other assertions I have chosen to focus on are assessed more effectively in relation to novice-expert studies. For this third line of evidence, Glaser cites work that is ongoing in problem solving in radiology and mechanics (within physics) in his own laboratories (See Lesgold, Feltovich, Glaser and Wang, 1981).

Consideration of Evidence Cited by Glaser

I have argued that the empirical evidence to support Glaser's claims ought to come from knowledge-rich domains of the curriculum - mathematics, science, social studies, and the like. Glaser, however, cites evidence from three sources - data and theory in developmental psychology, process analysis of intelligence and aptitude test tasks, and studies of expert and novice problem solving. Only the latter deals with knowledge-rich domains found in school curricula. Glaser entitles one section of his paper "The Focus on Knowledge", and in the sections's introductory paragraph he shifts emphasis from the previously highlighted interactions to "...a new dimension of difference between individuals who display more or less ability in thinking and problem solving... the possession and utilization of an organized body of conceptual and procedural knowledge..." (p. 97).

The first source of evidence is developmental studies by Chi (1978; Chi and Koeske, 1983) and by Carey (in press). Chi (1978) demonstrated that expert chess players who were children had far superior memory for chess positions than adults who knew little about chess; however, on a standard digit span task, the adults outperformed the children in a fashion consistent with typical digit span task findings. Chi did demonstrate that knowing more chess enabled the children to remember more chess piece positions, but not more sequenced digits, than adults. These data support the postulated interaction between knowledge and processing.

Glaser also cites Siegler's "rule assessment" approach to developmental change (Siegler & Klahr, 1982; Siegler & Richards, 1982). This is in an area related to science problem solving - balance scale tasks. A task analysis enabled Seigler to determine what cues were attended to by children. For example, five-year-olds encoded weight information, but failed to encode

distance information. Siegler then provided learning events that helped the child to acquire additional relevant knowledge, and with increasing knowledge children could exercise complex rules that applied to a larger set of problems.

The studies cited by Glaser definitely show that the acquisition of knowledge is a crucial aspect of development. These studies do not demonstrate that particular knowledge structures interact nonadditively with particular cognitive processes to produce different outcomes. The studies suggest that the knowledge base may influence what strategies are available for use and how problems are represented. If cognitive processes are equated with strategy use, then cognitive processes may be said to be influenced by knowledge structures.

The second line of Glaser's evidence is what he calls "Process Analysis of Aptitude and Intelligence". Here he cites his work with Pellegrino on inductive/analogical reasoning (Pellegrino & Glaser, 1982). They found several interrelated components of performance that differentiated high- and low-scoring individuals: speed of performance (perhaps reflecting management of working memory processes), knowledge of item content (meaning of words used in the analogies), and knowledge of solution procedures required for solving analogy-form reasoning tasks. This line of evidence is very much like the knowledge-lean studies Glaser refers to in the early sections of his paper and, like the heuristic studies, emphasizes the need for knowledge that is "constrained". Knowledge-lean problems can be contrasted with knowledge-rich problems. Knowledge-lean problems present most of the information necessary (generally not very much) for solution in the task space. Knowledge of a particular set of steps, that are not integrated with a network of concepts

and principles, is the key to solution. On the other hand, knowledge-rich problems present only a small part of the considerable amount of information necessary for solution, and the individual must introduce all the other inter-related information from long-term memory or from some external source. These data, if they are derived from knowledge-lean problems, will not necessarily hold true for knowledge-rich problems. Glaser, himself, argues this in the introductory section of his paper.

The third line of evidence is closest to knowledge-specific problem solving. This section of Glaser's paper is entitled "Problem Solving in Experts and Novices". Glaser begins

> Current studies of high levels of competence support the recommendation that an important focus for understanding expert thinking and problem solving is investigation of the characteristics and influence of organized knowledge structures acquired over long periods of learning and experience. (p. 98)

He goes on to discuss investigations that he has undertaken with Chi and Lesgold to construct a theory of expert problem solving and its acquisition based on empirical descriptions of novice and expert performance in complex knowledge domains. The domains under study are physics (particularly mechanics), and radiology (particularly the interpretation of x-rays). Their assumption is that the relation between the structure of the knowledge base and problem-solving process is mediated through the representation of the problem. They then list a number of assertions suggested to them by their current work about the characteristics of the expert and the novice. These assertions are discussed in the next section of the paper. Specifically, they are clarified, and translated into testable hypotheses or falsifiable statements. These can be compared with the body of existing literature on

expert and novice problem solving that Glaser only mentions in passing (e.g. Larkin, McDermott, Simon & Simon, 1980; Voss, Greene, Post & Penner, 1984). This literature does study knowledge-rich domains, three of which are explored later in this paper - science, mathematics, and social studies.

Translation into Hypotheses and Examination of Additional Data

Glaser's Assertions Stated as Six Testable Hypotheses

If Glaser's argument is to be supported, then his assertions must be translated into testable hypotheses or, if you will, falsifiable statements. These must be stated clearly so that they can be adjudicated in light of the existing research. First, six assertions that I gleaned from Glaser's paper, each concerning characteristics of expert problem solvers, will be discussed in general terms. What does each mean? Is it stated operationally enough to be tested or falsified? Are there existing supporting data of a general nature? After this general consideration, the empirical research will be examined seeking support for these assertions in three areas of problem solving that are a part of secondary school curricula - mathematics, science, social studies.

Glaser's first assertion is:

1. There are strong interactions between structures of knowledge and cognitive processes.

In order to make sense of this assertion, it is necessary to define the terms. To clarify what is meant by knowledge structures, Glaser introduces the theoretical concept of "prototypical knowledge structures of schemata." Schemata become theories held by individuals and tested in the course of solving problems. The manner in which an individual represents a problem to be solved is the observed indicator of the organized knowledge base, theory or schema. "Our assumption is that the relation between the structure of the

knowledge base and problem-solving process is mediated through the quality of the representation of the problem" (Glaser, 1984, p. 98).

Glaser does not provide a definition of cognitive processes. Cognitive processes are ordinarily considered to be any of a set of operations which can be performed regardless of content (e.g., rehearsal, discrimination, labelling) (Carroll, 1976: Winne, 1984).

Glaser's asssertion about interactions is open to interpretation. If he means "interactions" in the statistical sense, then particular "levels" of knowledge structures (e.g., well-organized and poorly-organized) ought to combine nonadditively (Loftus, 1978; Winer, 1971) with particular "levels" of cognitive processes (e.g., discrimination and generalization) to produce different outcomes on a dependent variable. For instance, people with organized knowledge structures might use discrimination to solve problems in mechanics, while people with poorly-organized knowledge structures might use labelling on the same task; but these groups, when required to use the other process, would not do well.

If, on the other hand, Glaser used the term interaction in a non-statistical manner, then it might be that the knowledge structures inform or influence what processes will be used, and that is all there is to be said. The latter seems unlikely in the context of a psychological paper. Other than in social psychology, interaction is usually employed in a statistical manner. Glaser failed to specify which interpretation he intended.

What evidence exists to support each interpretation? The evidence in support of the first interpretation of this assertion will be considered in the section entitled Evidence from Knowledge Domains Taught in Schools. There is some evidence to support the second interpretation of Glaser's assertion about interactions (Britton & Tesser, 1982). In this study, the authors

varied prior knowledge in problem solving (chess novices and experts), thinking, and reading tasks in three experiments. I will consider only the problem-solving experiment. In the problem-solving experiment, there were two tasks. The primary task was to recommend a move from a "middle game" position in a simulated chess game. The secondary task was reaction time to randomly spaced clicks. Prior knowledge was manipulated by comparing experts with novices. Experts had longer reaction times than novices on the secondary task. Britton and Tesser (1982) argued that the results showed less cognitive capacity for the secondary task on the part of the experts because they bring more prior knowledge to bear in solving problems. These results are consistent with the hypothesis that prior knowledge is used in an ongoing task. The prior knowledge might occupy capacity in the same limited system used to perform the experimental task. If available capacity in the limited system is more restricted for experts because of the larger allocation to prior knowledge, then options for processes are limited by the residual capacity. While the evidence is by no means conclusive, these results may correspond with my second interpretation of Glaser's assertion about interactions. Knowledge structures <u>may</u> influence which processes will be used.

The second of Glaser's assertions to be investigated is:

2. Better problem solvers are characterized by "possession and utilization of an organized body of conceptual and procedural knowledge".

This might mean that poor problem solvers are characterized as: (1) not <u>possessing</u> both conceptual and procedural knowledge; (2) not <u>utilizing</u> both conceptual and procedural knowledge; (3) lacking <u>organization</u> in both conceptual and procedural knowledge. It might also mean that any one or all

of the above statements are true with respect to only one of conceptual and procedural knowledge. This raises the question: which of these distinctions are necessary and which are contingent? Poor problem solvers may lack knowledge. It is possible that they possess but do not use an organized body of knowledge. This might be attributable to lack of metacognition, that is, not monitoring and regulating the application of the knowledge they have (Brown, Bransford, Ferrara & Campione, 1983). It could also be attributed to lack of motivation, that is, they could do the problem solving if they chose to. What the experimenter sees is that the poor problem solver does not solve, not that he cannot solve (Licht, 1983). They could have the requisite body of knowledge, but its disorganization may make it inaccessable. Is it conceptual knowledge that is lacking or have these concepts failed to be proceduralized (Anderson, Greeno, Kline & Neves, 1981)? Glaser implies that possessing and utilizing an organized body of both conceptual and procedural knowledge are all necessary for problem solving. Brown (in press) recommends that diagnosis may be necessary in order to locate the missing link(s) in this problem solving chain.

Perhaps support for this assertion about the knowledge of better problem solvers can be clarified by looking for differences in the use of problem representation by better and poorer problem solvers. Glaser's third and fourth assertions are relevant to such a discussion.

Glaser's third assertion is that:

3. "Knowledge of novices is organized around the literal objects given in the problem statement."

One question arises. Does Glaser really mean that the novice's knowledge base (structured network) is organized around literal objects found in the problem statement? Or does he mean that the novice's problem representation is

organized around the literal objects named in the problem? How would one ever discern the former, and wouldn't that give problem statements a major organizing role in knowledge? If Glaser meant problem representation this raises the issue of what it is that a problem's representation indicates for it gives an external observer access to at best a sample of knowledge organization from which generalizations can be made. It is important to investigate whether different problem forms such as algebra word problems and algebra equation problems (Mayer, 1982) elicit different representations. Problem representation may itself be a "construction" resulting from the interaction of knowledge structures/network and the question posed, instead of a simple reflection of a portion of the network. The statement seems more supportable if it is "Problem representation of novices is organized around the literal objects given in the problem statement."

Consider the obverse of the previous assertion, Glaser's fourth assertion that:

4. "Experts' knowledge is organized around principles and abstractions that subsume these objects."

Once again the question arises as to whether the most appropriate variable to consider is the organization of knowledge or the organization of problem representation. As in the case of the previous assertion, the evidence from problem-solving studies in three curricular areas will be considered to see whether either the stronger statement of knowledge organization or the weaker statement about organization of problem representation can be supported by studies already conducted.

Glaser makes the fifth assertion that:

5. "Novices show effective heuristics."

Clarification needs to be made as to whether Glaser meant that novices have effective heuristics - or whether novices show effective use of heuristics. Does this imply that an examination of empirical studies will reveal no significant differences in possession of and/or utilization of general problem solving heuristics between novices and experts in knowledge-domain problem solving? Which heuristics ought one to examine - means-end analysis, setting sub-goals? Studies of novice problem solving in science, mathematics and social studies will be examined to discern the extent of support for this fifth assertion.

Glaser's sixth assetion to be considered is:

6. Novices show "inability to infer further knowledge from the literal cues in the problem statement."

Are the cues perceived as cues from which knowledge or information can be inferred by the novices or are they perceived as information with no inferential value? It is possible that novices perceive the cues as cues with inferential value but do not know the other things needed to make the inference. Research in problem solving will be examined to see whether it substantiates any of the interpretations of Glaser's sixth assertion.

These specific assertions were selected from Glaser's paper because his paper is seen by this author to be about "Instruction in Problem Solving: The Role of Knowledge". These assertions of Glaser's about the role of knowledge in problem solving require support because they are the foundation upon which the implications for instruction are built. However, Glaser's indefinite statements of these assertions require discussion and some clarification before they can be considered testable hypotheses. These clarifications are intended to help prepare the way for the consideration of evidence from the problem-solving research in each of the three curricular areas of mathematics, science, and social studies (See Table 1).

Evidence from Knowledge Domains Taught in Schools

Physics. Physics problems have been presented to novices and experts to solve and to categorize, and think-aloud protocols have been recorded for analysis (Chi, Feltovich & Glaser, 1981; Simon & Simon, 1978). As well, analyses that yield prescriptions for instruction have been conducted of the kinds of knowledge and procedures leading to effective problem solving in physics (Reif & Heller, 1982).

Simon and Simon (1978) compared the performances and protocols of an expert (with strong mathematical skills and extensive experience in solving problems in mechanics) with a novice who had fair skills in algebra but had only recently studied kinematics. Each read a chapter of a physics text, answered some questions about the chapter and worked 25 problems. They talked aloud to generate protocols while solving problems such as:

> A bullet leaves the muzzle of a gun at a speed of 400 M/Sec. The length of the gun barrel is 0.5 M. Assuming the bullet is uniformly accelerated, what is the average speed within the barrel?

The expert solved such problems in less than one quarter of the time required by the novice and with fewer errors. Examination of the think aloud protocols and worksheets also revealed strategic differences. The expert worked forward from the givens to the desired quantities while the novice frequently solved problems by working backward from the unknown problem solution to the given quantities. The study's authors interpreted this to mean that the novice needed subgoals to direct the search, and may have been resorting to more general heuristics, perhaps overburdening limited short-term memory. This supports Glaser's assertion about novices using heuristics effectively, to the extent that novices use heuristics. The question remains whether they use them effectively. Perhaps novices use heuristics because

they don't have the more directly applicable knowledge that is available to the expert, even if the heuristics are not really effective. This suggests that resorting to heuristics may result from lack of effective procedural knowledge. This lends support to Glaser's assertion about experts being characterized by possession and utilization of an organized body of conceptual and procedural knowledge.

An additional difference was that the expert performed "steps" or expressed in a single verbalization what would have been three separate verbalized steps for the novice; for example, an expert would evoke a formula, put it in appropriate form, and substitute numerical values for givens. The novice required reference to goals or cueing from symbols written on the worksheet. The procedures employed by the two differed in how they could be represented in production systems or series of condition-action statements. For the expert, the condition for solving was that the values of all the independent variables had to be known, while the novice needed this condition fulfilled, and also, for the novice, the dependent variable of the production's formula had to be one of the variables that they needed to calculate. If we accept the nonstatistical interpretation of Glaser's assertion about interactions then knowledge appears to influence or inform production systems. Could Glaser have equated production systems to cognitive processing? If so, we have data to suggest his first assertion is tenable.

Chi et al. (1981) investigated the categorization and representation of physics problems by experts and novices in a series of four studies. They did not investigate directly the "cognitive processes" of their subjects, so it is impossible to find direct support for the first interpretation (statistical) of Glaser's premise about interactions between structures of knowledge and cognitive processes. (Although it is difficult to know what Glaser meant by

cognitive processes, when he failed to provide a definition.) The findings of study 1 indicated that experts (advanced Ph.D. candidates) took longer than novices to sort 24 problems into categories. This was the reverse of Simon and Simon's (1978) finding for solving. Experts classified according to the major physics principle governing the solution of each problem, e.g. grouping problems that could be solved by applying Newton's second law. Novices classified according to keywords or visual configurations present in the problem statement.

With regard to the premise that better problem solvers are characterized by the possession and utilization of an organized body of conceptual and procedural knowledge, these findings are relevant. Both groups (experts and novices) categorized problems according to an organizational plan. This organization was elicited through think aloud protocols in study 3. Two novices and two experts were given three minutes to tell everything they could about problems involving each of 20 category labels. The novice's protocols generated network representations consisting mainly of variables with a passing reference made to principles. The expert protocols generated network representations that began with general principles, contained the conditions under which the principles applied, and then contained the variables that made up the novices' representation. The expert representations contained production rules of the form "if...then...". This means that they incorporated procedures leading to actions, which were missing from the novice protocols. Concerning the second premise - both expert and novice problem solvers possessed and utilized an organized body of conceptual knowledge, although the two appeared to be organized differently, and experts did have more knowledge. The experts demonstrated that they possessed and utilized procedural knowledge that was conditional in nature. This was not evident in the protocols of the novice problem solvers.

The premise that knowledge of novices is organized around the literal objects given in the problem statement was demonstrated in study 1 where the task was sorting problems, and study 2 where one novice, advanced novice, and expert each categorized problems specially designed to have surface features roughly crossed with applicable physics laws. Correspondingly, the premise that the knowledge of experts is organized around principles and abstractions that subsume the objects mentioned by novices is likewise demonstrated by study 1 and study 2. There is, however, no data provided in these four studies to evaluate the claim that novices show effective heuristics, nor any data to adjudicate the comparative use of heuristics by novice and expert problem solvers.

The last claim of Glaser's to be considered is that novices show "inability to infer further knowledge from the literal cues in the problem statement". In study 4, two experts and two novices thought aloud their "basic approaches" to solving problems. Then they were asked to state explicitly the problem features that led to their choice. The novices gave general solution methods and formulae, and reported that the features cueing them were literal terms and objects in the problem statement, such as "friction" and "gravity".

On the other hand, the expert problem solvers interpreted "basic approaches" as the major scientific principles they would apply to solve the problems. They identified descriptions of states and conditions of physical situations described by the problem. These were second order features not named in the problem statement. Does this support the claim that novices showed "inability to infer from literal cues"? Did the novices fail to perceive the cues as cues? Did they perceive them but not know other things needed to make use of them? The novices perceived the cues (literal features)

as the features that identify problem categorization and representation. These cues stimulated them to carry out bottom-up processing moving from literal variables to equations containing these variables, to solutions arrived at by manipulating equations and variables. The expert problem solvers used the cues (perhaps automatically) to trigger hypotheses about the principles involved, and then set out processing from the top-down, from the principles (schemata) and filling slots with transformations of literal features. Novices inferred from literal cues. However, they inferred fragmented organizations, such as formulae, rather than general principles. Do these fragmented organizations constitute knowledge when they are not schemata for principles, but are merely specifics?

It is important to note that these problem solvers only categorized and represented problem statements. They did not solve the problems. Their sorting behavior and think-aloud protocols were not generated during problem solution.

Reif and Heller (1982) addressed Glaser's concern about the role of knowledge structure in problem solving in physics. They have not concentrated on the investigation of naturally occurring intellectual functioning in experts, but have sought to answer the following general question: What kinds of knowledge and procedures enable humans to achieve good problem solving performance in a realistic scientific domain? Their task analysis indicates the importance of a knowledge base containing substantial amounts of specialized knowledge, organized in a hierarchical fashion to facilitate efficient retrieval and problem solving. Each level of the hierarchy elaborates on the level above it, providing more detail about the conditions under which relations and interactions take place. The factual knowledge in the knowledge base is accompanied by explicit "application guidelines" which include ancillary factual and procedural information.

Reif and Heller's task analysis of adequate problem solving in mechanics suggests that the knowledge base is used in conjunction with general procedures. They concentrate on three kinds of procedures. The first are procedures for describing and analyzing any problem with the aid of the knowledge base, to bring it into a form facilitating solution. The second are methods used in the "search and decision processes" or procedures needed to construct the solution. The third are procedures to test whether the solution is correct and optimal so that appropriate revisions can be made.

This model makes explicit the processing that the authors think goes into expert problem solving, even though experts appear to carry out many of these procedures automatically, rapidly, without conscious effort, perhaps using tacit knowledge.

> For instance, observations ... indicate that experts rapidly redescribe problems presented to them, often use qualitative arguments to plan solutions before elaborating them in greater mathematical details, and make many decisions by first exploring their consequences. Furthermore, the underlying knowledge of such experts appears to be tightly structured in hierarchical fashion. (Reif & Heller, 1982, p. 123)

In summary, an examination of three papers related to problem solving in physics indicates that very little of the data actually comes from problem-solving protocols. Most of it is generated in tasks requiring subjects to classify problems. Within this limitation, there is considerable support for Glaser's distinction between novices organizing their representations around literal objects, and experts organizing their representations around principles and abstractions. It appears that novices do use heuristics (although a judgment of effectiveness is unwarranted), and knowledge does

appear to inform or influence production systems, although it is uncertain whether this is what Glaser meant by his assertion that knowledge and cognitive processes interact. The most thorough and most supportive study was conducted by Glaser and his colleagues. Perhaps the strength of his own findings encouraged him to overgeneralize.

Mathematics. Empirical investigations have been conducted on the perception or representation of mathematical problems. Hinsley, Hayes, and Simon (1977) investigated perceptions of whether problems were related in high school and college students chosen for their knowledge of algebra. These competent mathematics students sorted a collection of typical algebra verbal problems into groups of related problems. There was considerable agreement among the students on 16 distinct categories or problem types (e.g., distance/rate/time, mixture). Subjects were able to categorize a problem almost immediately, after hearing only the first few words, and tended to use problem categorization to assist in retrieving useful information from long term memory.

This is not a contrastive study of novices and experts, but rather a descriptive account of the perception or representation of problem relatedness in competent mathematics students in high school and college. Because "novice" and "expert" are relative terms defined by contrast, it is impossible to classify these subjects. However, it does demonstrate that their perceptions are quite consistent. The study has been cited frequently as the first study in mathematics to demonstrate "prototypical knowledge structures or schemata". The existence of such structures is not sufficient to substantiate Glaser's first claim that they interact with cognitive processes in a nonadditive manner to influence problem solutions, although in the less stringent interpretation, they appear to influence discrimination (a cognitive

process) of similarity in problem types. Their quick, consistent, responses could be intepreted to reflect possession and utilization of organized knowledge, or to merely reflect well-formed, isolated associations. This doesn't help us to confirm Glaser's assertion about the organized knowledge possessed by experts. Although they were considered to be competent (and perhaps by extension, "expert") mathematics students, their categorization, sometimes based on a few words of the problem, can be interpreted to mean that their problem representation (if not their knowledge) was "organized around the literal objects given in the problem statement". This would seem to contradict Glaser's assertions that novices organize by surface structure while experts organize by deep structure. They were provided with little opportunity to show their use of heuristics, and shed no light on Glaser's assertion that novices use heuristics effectively. It is difficult to consider their actions as support for Glaser's contention that novices are unable to infer further knowledge from literal cues, as this group was chosen on the basis of their proficiency, but responded to literal objects like novices, and rapidly made inferences on the basis of these literal objects.

Silver (1979) had 156 junior high school students partition a collection of verbal problems into subsets which they judged to be mathematically related. The extent to which a student sorted problems on the basis of the mathematical stucture of the problem was related significantly to the individuals's problem solving ability. The less capable junior high school students appeared to have organized their problem representations (and perhaps might have formed their schemata) not on mathematical structures, but on less useful criteria such as contextual details or question form. Once again, this is not a contrastive expert-novice study, and thus it is a bit difficult to fit the findings to Glaser's assertions. Better problem solvers probably did

have more knowledge (an assumption) and did make different discriminations or judgments of similarity, so this could be taken as weak support for Glaser's assertion about interactions. The subjects did not solve problems or generate protocols, so one must exercise caution in considering their responses as telling us about their organized body of conceptual and procedural knowledge. However, the findings do support Glaser's assertions that less competent or novice problem solvers responded to surface structure, while the more competent sorted on the basis of deep structure or method of solution. If surface structure were a reliable indicator of deep structure, then the differences between novices and experts would not be as distinct. However, surface structures do not always point to the same deep structures.

Schoenfeld and Herrmann (1982) investigated college students' perceptions of the structure of mathematical problems before and after a month-long intensive course on problem solving. These perceptions were compared with those of experts. Subjects sorted problems on the basis of similarity. Hierarchical clustering analysis of the sorting data indicated that novices or students about to begin the course perceived problems on the basis of "surface structure", that is, words or objects described in the problem statement. After the course the students perceived problems to be related according to the mathematical methods relevant for solving the problems, like the experts. A control group composed of students who were taking a month-long intensive course in computer programming also sorted the problems on the basis of similarity before and after the course. There was little change in their sorting from the first to the second sort. The authors concluded that "students' problem perceptions change as the students acquire problem-solving expertise" (Schoenfeld & Herrmann, 1982, p. 491).

The obvious interpretation of these data has to do with how the problems are represented by the so-called novices and experts - the shift that accompanied improvement in problem solving from sorting problems by "surface structures" to sorting problems by "deep structure", is directly supportive of Glaser's assertions about the organization of knowledge. However, these studies do not fully address or support others of Glaser's assertions.

It is important to keep in mind when considering these three studies from mathematics that none was a classic contrastive study, so they do not lend themselves easily to support Glaser's generalizations. None of the three was really a study of how people solve problems, but rather of how people sort problems which is assumed to reveal the organization of their knowledge structures. This sample may simply reflect their representation of the particular problems presented, because the problems may not elicit the individual's entire relevant knowledge structures.

Social Studies. Some of the problems that confront students in their lives are well structured like mathematics and science problems. Other problems that societies and individuals must solve are not as clearly defined and are more like those presented to students in social studies (Frederiksen, 1984). In social science, a problem exists "when there is an undesirable state of affairs that requires improvement" (Voss, Tyler, & Yengo, 1983). Recent studies have investigated the role of knowledge and attitude in prose processing of potentially controversial social studies material (Tyler & Voss, 1982). They have also studied the differences in novice and expert think-aloud protocols of solutions to problems in social studies (Voss et al., 1983; Voss et al., 1984).

In mathematics and science problem solving, there is little dispute over the facts presented in the problem, or about what constitutes an expert

solution. However in social studies, there is frequently controversy about both the presenting data and the definition of an adequate solution. It is possible that attitudes, as well as knowledge, influence problem solving and processing. Tyler and Voss (1982) studied the effects of attitude and knowledge on prose processing in the content domain of international politics, more specifically, the Soviet Union and its relations with other countries. They used questionnaires to assess knowledge about and attitudes toward the U.S.S.R. of 41 students ranging from introductory to advanced political science students. The students rated the friendliness of relations of various countries with the U.S.S.R. and listened to passages about soviet relations. Finally the students rated the aggressiveness of these passages and then completed recall and recognition tests about them. The findings were interpreted as suggesting that knowledge dominates processing when passage contents are high in information value and/or disagree with expectations. Attitude, on the other hand, was seen to dominate processing when passage contents were of low information value and in agreement with expectations.

While the introduction of attitude does not clarify the role of knowledge in problem solving, it does remind one to keep the influence of attitude in mind. The other two papers by Voss and his colleagues consist of analyses of the same protocol data by two different systems.

In the first paper, Voss et al. (1983) present the problem that:

> In the Soviet Union, agricultural productivity has been quite poor in the last five years and, assuming that you are the head of the USSR Ministry of Agriculture, you must improve that productivity. The question is, how would you solve the problem? (p. 208)

Four university professors whose field of expertise was the Soviet Union and six undergraduate students taking a course on Soviet domestic policy thought-aloud during the solving of this problem. Protocols were also obtained from faculty members with expertise in Latin America and in chemistry. As no widely accepted method of evaluating solutions was available, the authors segmented protocols into constituent argument units, classified the units into Toulmin's argument categories (e.g., datum, claim, warrant, backing, qualifier, rebuttal). Comparisons were made. The novices made many claims about solutions, with little backing, and few data. The experts made few claims, with long chains of argument providing extensive data, warrants, backing and even qualifiers and rebuttal. The experts devoted a relatively large proportion (approximately 24%) of the protocol to developing a representation of the problem using the categories other than claim. They made considerable use of constraints (such as Soviet ideology, amount of arable land). They usually delineated the problem space sufficiently to classify the problem in terms of some particular abstract cause. This specification (technological, social, political) for different experts, set the orientation from which the broad, encompassing solution followed.

The novices, on the other hand, spent little time developing their representations, but went straight to work discussing possible solutions. The series of piecemeal solutions frequently were inconsistent with one another, and showed little consideration for constraints. Claims were over-represented with little use of argument.

The politial scientists (who were not experts on the U.S.S.R.) generated problem representations, used general constraints such as knowledge of government operations, and ended up with a representation similar to that of the experts. One chemist solved like the political scientists while the other three produced protocols and solutions similar to those of the novices.

The authors of these articles raised a number of methodological and conceptual issues, related to their dissatisfaction with the jurisprudence model of Toulmin. Voss et al. (1984) reanalyzed the protocol data using a model with two structures - a problem-solving control structure, and a reasoning structure, each with its own set of operators. The re-analysis permitted a slightly different interpretation of the clear differences between experts and novices. The experts clearly explored the ramifications of the proposed solutions and presented extensive supportive argument. They sought one general solution which would provide solutions to all the sub problems in ways that were not contradictory. Novice protocols were characterized by problem decomposition with solutions proposed for many low-level sub problems, such as to get more tractors or to get more fertilizer. They were also characterized by lack of argument, and lack of consideration for constraints. Although evaluation of problem solutions in the social sciences is different in many ways, as discussed by Voss and his colleagues, there are surprising similarities with the problem-solving data from physics and mathematics.

Summary of evidence from three knowledge domains. In the three curricular areas examined, the differences between novices and experts point to a relationship between structures of knowledge and cognitive processes. The nature of that relationship is unclear, although it appears that knowledge influences processing. Better problem solvers in the three areas do show better use of conceptual and procedural knowledge, although this appears to differ among knowledge domains. According to Schoenfeld and Herrmann:

> ...elementary physics is strongly principle-driven, and the subject matter is organized and taught according to those principles. Mathematics is not organized that way, however. One talks about methods of solution, rather than principles;

> and the curriculum is organized around topics rather than around those methods, which are simply the tools used to solve them. (1982, p. 490)

In the social science investigations, organizing concepts appeared to play a major role. We lack the data to confirm that experts possess and utilize an organized body of conceptual and procedural knowledge, while the contrastive group does not. The statement is too sweeping to be supported. However, there is strong support for the assertions that novices form initial problem representations around surface structures of problems, and experts represent problems in terms of deep structures. This does not necessarily mean that all relevant knowledge of problem solvers is organized in these ways. These data suggest that novices use heuristics, probably in the absence of more effective strategies. The final assertion, that novices fail to infer further knowledge from cues, remains unsupported rather than disproved.

Limitations of contrastive studies employing protocols. Verbal reports (including think-aloud protocols) have been criticized as incomplete, as being altered by the instructions given, as unreliable and idiosyncratic because they do not carry any information that is generalizable or that can further our understanding of performance (Nisbett & Wilson, 1977).

Ericsson and Simon (1984) have argued that subjects should verbalize their thoughts at the time they emerge. Then the difficulties and sources of error associated with keeping thoughts in memory or retrieving them from memory could be eliminated. They assert that the "think aloud" or "talk aloud" method did not produce a real breakthrough until the verbalized information could be given explicit meaning in terms of a formal model of the thought processes that could be simulated on a computer (Ernst & Newell, 1969).

A recent criticism has been that giving verbalizations concurrently with the cognitive processes changes the performance and hence the cognitive processes studied ("effect-of-verbalization" argument). Similarly, knowing one will be asked to give a retrospective report after the experiment has been suggested to alter the processing under study. A second criticism is that the subject may fail to verbalize much of the information that he uses in the task he is performing, perhaps he can't heed it all, or may lack knowledge or memory of some of the relevant activities. This is the "incompleteness" argument. Finally there is the "irrelevance" argument, that the verbalizations may report an activity that occurs in parallel with, but independent of, the actual thought process. Each of these criticisms is met and dealt with in Protocol Analysis: Verbal Reports as Data (Ericsson & Simon, 1984). The authors recommend cross-validation of verbal reports (in protocols) with other measures such as problem solutions written out and retrospective recall. One might also be able to cross-validate by collecting what Winne (1984) has called observable "traces" of hypothesized cognitive activity. These records should be collected during instruction, perhaps on a worksheet. They should be unobtrusive with respect to medium and time, easy to train students to exhibit, and valid reflections of cognitive operations. The major difficulty remains that any and all of these measures may be substantially changing or disrupting what it is they are trying to understand.

Although expert-novice contrastive studies do show some differences between novices and experts, the design of these studies precludes unequivocal conclusions about the origins of these differences. What is needed are instructional studies that document the role of domain-knowledge structures in the transition from novice to expert (or competent). One confounding factor in existing studies is that relative to novices, experts are usually older, more trained, and most likely more motivated. Schoenfeld and Herrmann's

(1982) study attempts to overcome this problem by examining problem representations in individuals who were given training, and comparing them to a control group of similar aptitude.

It is perhaps unwise to assume that our goal is to teach students to perform as experts do, especially when experts perform automatically things we must teach students to do explicitly. Reif and Heller (1982) suggest that it is unwise to assume that the performance of an expert is necessarily optimal. As well, many of these investigations employ small samples (sometimes only one expert) in what are essentially correlational studies.

Concluding Statement

Glaser's paper "Education and Thinking: The Role of Knowledge" presents a series of hypotheses for future research. Some of these hypotheses, as I have shown, have received tentative support from the novice-expert studies in three curricular areas; however, much more research is needed in order to make the definitive statements that characterize Glaser's (1984) paper. It would be premature to significantly alter instructional practices for millions of North American pupils on the basis of Glaser's assertions. Correlational studies based on small numbers of experts and novices do not provide adequate support for the kind of causal relationship that Glaser concludes exists between the acquisition of problem-solving skills and the integration of their instruction with domain knowledge. Further investigations comparing the effectiveness of problem solving instruction when integrated with domain-specific knowledge in various curricular areas are necessary. As well, it is important to investigate the influence that metacognitive processing may exert over both the knowledge structures and the cognitive processing of which Glaser speaks.

References

Anderson, J.R., Greeno, J.G., Kline, P.J. & Neves, D.M. (1981). In J.R. Anderson (Ed.), Cognitive skills and their acquisition. Hillsdale, NJ: Erlbaum.

Britton, B.K. and Tesser, A. (1982). Effects of prior knowledge on use of cognitive capacity in three complex cognitive tasks. Journal of Verbal Learning and Verbal Behavior, 21, 421-436.

Brown, A.L. (in press). The importance of diagnosis in cognitive skill instruction. In S.F. Chipman, J.W. Segal & R. Glaser (Eds.), Thinking and learning skills: Current research and open questions (Vol.2). Hillsdale, NJ: Erlbaum.

Brown, A.L., Bransford, J.D., Ferrara, R.A. & Campione, J. (1983). Learning, remembering and understanding. In J.H. Flavell & E.M. Markman (Eds.). Carmichael's manual of child psychology. (Vol. 1). New York: Wiley.

Carey, S. (in press). Are children fundamentally different kinds of thinkers and learners than adults? In S.F. Chipman, J.W. Segal, & R. Glaser (Eds.), Thinking and learning skills: Current research and open questions (Vol. 2). Hillsdale, NJ: Erlbaum.

Carroll, J.B. (1976). Psychometric tests as cognitive tasks: A new "Structure of the intellect?" In L.B. Resnick (Ed.), The nature of intelligence. Hillsdale, NJ: Erlbaum.

Chi, M.T.H. (1978). Knowledge structures and memory development. In R. Siegler (Ed.), Children's thinking: What develops? Hillsdale, NJ: Erlbaum.

Chi, M.T.H., Feltovich, P.J. & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. Cognitive Science, 5, 121-152.

Chi, M.T.H. & Koeske, R.D. (1983). Network representation of a child's dinosaur knowledge. Developmental Psychology, 19, 29-39.

Ericsson, K.A. & Simon, H.A. (1984). Protocol analysis: Verbal reports as data. Cambridge, Massachusetts: MIT Press.

Ernst, G.W. & Newell, A. (1969). GPS: A case study in generality and problem solving. New York: Academic Press.

Frederiksen, N. (1984). Implications of cognitive theory for instruction in problem solving. Review of Educational Research, 54, 363-408.

Glaser, R. (1984). Education and thinking: The role of knowledge. American Psychologist, 39, 93-104.

Greeno, J.G. (1980). Trends in the theory of knowledge for problem solving. In D.T. Tuma & F. Reif (Eds.), Problem solving and education. Hillsdale, NJ: Erlbaum.

Hinsley, D.A., Hayes, J.R., & Simon, H.A. (1977). From words to equations: Meaning and representation in algebra word problems. In P.A. Carpenter and M.A. Just (Eds.), Cognitive processes in comprehension. Hillsdale, NJ: Erlbaum.

Larkin, J. (1980). Teaching problem solving in physics. In D.T. Tuma & F. Reif (Eds.), Problem solving and education. Hillsdale, NJ: Erlbaum.

Larkin, J.H., McDermott, J., Simon, D.P. & Simon, H.A. (1980). Models of competence in solving physics problems. Cognitive Science, 4, 317-345

Lesgold, A.M., Feltovich, P.J., Glaser, R. & Wang, Y. (1981). The acquisition of perceptual diagnostic skill in radiology. (Tech. Rep. PDS-1). Pittsburgh, PA: Learning Research and Development Center, University of Pittsburgh.

Licht, B.G. (1983). Cognitive-motivational factors that contribute to the achievement of learning disabled children. Journal of Learning Disabilities, 16, 483-490

Loftus, G.R. (1978). On interpretation of interactions. Memory and Cognition, 6, 312-319

Mayer, R.E. (1982). Different problem-solving strategies for algebra word and equation problems. Journal of Experimental Psychology: Learning, Memory, and Cognition, 8, 448-462

National Assessment of Educational Progress. (1981). Three national assessments of reading: Changes in performance, 1970-80 (Rep. No. 11-R-01). Denver, CO: Education Commission of the States.

Newell, A. (1980). One final word. In D.T. Tuma & F. Reif (Eds.), Problem solving and education. Hillsdale, NJ: Erlbaum.

Nisbett, R.E. & Wilson, T.D. (1977). Telling more than we can know: Verbal reports on mental processes. Psychological Review, 84, 231-259

Pellegrino, J.W. & Glaser, R. (1982). Analysing aptitudes for learning: Inductive reasoning. In R. Glaser (Ed.), Advances in instructional psychology (Vol.2, pp. 269-345). Hillsdale, NJ: Erlbaum,

Polya, G. (1981). Mathematical discovery: On understanding, learning and teaching problem solving. Toronto: Wiley.

Reif, F. & Heller, J.I. (1982). Knowledge structure and problem solving in physics. Educational Psychologist, 17, 102-127.

Schoenfeld, A.H. & Herrman, D.J. (1982). Problem perception and knowledge structure in expert and novice mathematical problem solvers. Journal of Experimental Psychology: Learning Memory and Cognition, 8, 484-494.

Siegler, R.S. & Klahr, D. (1982). When do children learn? The relationship between existing knowledge and the acquisition of new knowledge. In R. Glaser (Ed.). Advances in instruction psychology. (Vol.2). Hillsdale, NJ: Erlbaum.

Siegler, R.S. & Richards, D.D. (1982). The development of intelligence. In R.J. Sternberg (Ed.). Handbook of human intelligence. Cambridge, England: Cambridge University Press.

Silver, E.A. (1979). Student perceptions of relatedness among mathematical verbal problems. Journal for Research in Mathematics Education, 10, 195-210

Simon, D.P. (1980). Problem solving and education. In D.T. Tuma & F. Reif (Eds.), Problem solving and education. Hillsdale, NJ: Erlbaum.

Simon, D.P. & Simon, H.A. (1978). Individual differences in solving physics problems. In R.D. Siegler (Ed.), Children's thinking: What develops? Hillsdale, NJ: Erlbaum.

Tuma, D.T. & Reif, F. (Eds.). (1980). Problem solving and education: Issues in teaching and research. Hillsdale, NJ: Erlbaum.

Tyler, S.W. & Voss, J.F. (1982). Attitude and knowledge effects in prose processing. Journal of Verbal Learning and Verbal Behavior, 21, 524-538

Voss, J.F., Greene, T.R., Post, T.A. & Penner, B.C. (1984) Problem solving skill in the social sciences. In G. Bower (Ed.), The psychology of learning and motivation: Advances in research theory. New York: Academic Press.

Voss, J.F., Tyler, S.W. & Yengo, L.A. (1983). Individual differences in the solving of social science problems. In R. Dillon & S. Schmech (Eds.), Individual differences in cognition. New York: Academic Press.

Wickelgren, W.A. (1974). How to solve problems: Elements of a theory of problems and problem solving. San Francisco: Freeman.

Winer,B.J. (1971). Statistical principles in experimental design (2nd ed.). New York: McGraw Hill.

Winne, P.H. (1984). Methodology for theoretical research, student cognition and achievement. Instructional Psychology Research Group Occasional Paper 84-01. Simon Fraser University, Burnaby, B.C.